Fabrication and Repair Research for Our Future in Space

Summer 2003 Workshop Implementation Plan

July 8 - 10, 2003

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Introduction

- **This workshop is one in a planned series of meetings extending over few years that are examining the subject of "In-Space Fabrication and Repair Research"**
- **The general focus of the workshop is to emphasize materials research under microgravity conditions to identify and assess innovative architectures, revolutionary concepts and technology needs and opportunities for a wide range of prospective future exploration and development of space activities**
- **The objective of this workshop is to generate a roadmap with specific goals in appropriate select topic areas to establish, develop, and mature In-Space Fabrication and Repair research.**
  - This roadmap will be used to direct new efforts for new materials science in those topic areas of greatest benefit to the Agency and its Enterprises . The product of this workshop would be a set of updated and expanded Technology Investment/Assessment criteria, and could become an input for a strategic plan for In-Space Fabrication and Repair Technology Development for our future In-Space. The Strategic Product is a step by step milestones, leading to a long-term capabilities for the agency over the next decade. The results obtained would reviewed and updated periodically in the future. Broad capabilities are sought (NASA, other government and non-government), rather than on specific missions, instruments, etc.
- **This meeting will examine a broader scope of prospective topic areas, with the goal of conceptually formulating notional "road maps" that could lead to the accelerated and ongoing realization of Fabrication and Repair capabilities, beginning in the middle years of the next decade…**

Fabrication and Repair Research (F&RR) Workshop Objectives

- **Review of concepts, plans, road maps, and analyses including**
    - Develop concepts for "Fabrication and Repair Research Options"
    - Review and collect current fabrication and repair Advanced Systems concepts, technologies, and research and analysis strategic road maps that capture information on technology metrics for a wide range of research and development options
    - Strategic planning for In-Space capabilities--focusing on areas where synergism between projected enabling research capabilities and candidate future space missions — including exploration, development, etc. applications— is strong
    - Candidate scenarios and/or architectures and systems concepts, including Human and Robotics supported capabilities based on strong understanding of materials and fabrications behavior and performance under microgravity
- **Formulation of road maps, including**
    - Adjustments to incorporate a new concept for accelerating and better synchronizing the pace of progress in space --
    - Identification and incorporation of breakthrough and/or key technologies
    - Identification of key technology metrics (e.g., updated assessments of parametric limits and/or 'boundary conditions" on surmounting Advanced Materials challenges)
    - Conceptual designs and analysis of innovative architectures/advanced systems for the development of an In-Space capability (that support identified exploration and space science utilization scenarios/cases)

F&RR Workshop
Objectives (continued)

- **Identification of advanced research and high-risk/high-leverage technology development and validation opportunities in the following Working Groups:**
  - Materials and Processes in Support for Fabrication
  - In-space Resources and Utilization in Support of Fabrication and Repair
  - Repair Tools, Research, Concepts, Facilities, and Technologies

- **Planned Workshop Products**
  - A summary report
  - Presentations prepared for the workshop
  - Reports from each Working Session, will include:
    - a summary view graph of all presentations in that session (electronic please)
    - research and technology development roadmaps
    - conceptual designs, concepts, data base of the state-of-the-art

Working Group 1
In Space Fabrication

- **The ability to reconfigure and/or evolve future space systems throughout the Earth's neighborhood and beyond is a critical capability needed to realize the goals of in-space ultra-long life systems**
- **This working session will review both current and planned practices and activities in this area, with an eye toward identifying material research challenges and approaches to solving them.**
- **Generate findings and make recommendations for further discussion**
- **Areas for discussion should include**
  - The central conceptual "drivers" that must be addressed to understand materials behavior, interactions, stability and properties under microgravity conditions
  - Materials Modeling, and its appropriate role in overall fabrication or repair
  - General discussion of various types of materials concepts and behavior such as hybrid-materials, filaments, thin films, free forming, nanotubes, etc.; identification of ongoing concept studies, programs, promise or lack of promise, etc.
  - Longer term and/or more generic advanced / supporting technology research topic areas
  - Research and Technology development Roadmaps

Working Group1

In Space Fabrication

- **Present Programs and activities, nationally and internationally**
- **Supporting Research and Technology with special emphasis on unique properties under microgravity**
- **Fabrication techniques such as electron beam, laser welding, free-form fabrication, etc.**
- **Thin films, layered structures, hybrid materials, amorphous structures, etc.**
- **Development of new materials favored by micro-gravity conditions**
- **Research Facilities**
- **Other Areas?**

Working Group 2

In-Space Resources and Utilization

- **A fundamental requirement to achieve fabrication and repair capabilities in space is the realization of the full potential of existing space "resources" infrastructures and systems, rather than importing the materials from Earth**
- **This concept involves onboard harvesting, mining, purifying, and processing any materials that can be critical in developing a capability in space …..regoliths to form photovoltaic cells, etc.**
- **This working session will review both current and planned developments in in this area, with an eye toward identifying challenges and approaches to harvest, process, and use these materials**
- **The working session should generate findings and make recommendations for further discussion**
- **Areas for discussion should include**
  - Materials identifications
  - Material processing and transformation -- including cryogenic chemical propulsion and electric/electromagnetic propulsion (including the concept of the Hybrid Propellant Module), infrastructure elements including radiation shielding,structural materials
  - Cryogenic propellants/fluids storage, management, transfer, etc.
  - "Revolutionary" approaches to material transfer and storage -- capable of application at various scales and over various locations
  - Research and Technology development Roadmaps
  - Other topics?

Working Group 2

In-Space Resources and Utilization
Work Breakdown Structure Areas

- **Space Resources Identification**
- **Space Resources harvesting, collection, mining**
- **Space Resources transformation and conditioning)**
  - In Space Propulsion (Electric/Electromagnetic)
  - In Space Propulsion (Chemical) – Particularly Cryogenic
  - Materials for fabrication
  - Materials for repairs
  - Materials for habitats, life sustenance, radiation protections
- **Space resources utilization and products generation**
- **Other areas?**

Working Group 3
In-Space Repair Research and Systems

- **In order to undertake very ambitious repairs research in the future—and to do so in a way that is safe, effective, affordable, and sustainable—a revolutionary new generation of materials, techniques, and space systems will be needed. The ability to return existing systems and assets to their original or enhanced operability and functionality by eliminating the effect of any damage is a critical capability needed to realize the goals of future in-space ultra-long life systems**
- **In addition, increasing levels of self-sufficiency, self diagnostics, self healing will be important to reduce the cost of operations, while continuing to extend activities.**
- **This working session will review both current and planned programs and activities in this area with an eye toward identifying challenges and approaches to solving them**
- **The working session should generate findings and make recommendations for further discussion**
- **Areas for discussion should include**
  - The concept of long-lived modular space systems – where modularity may be manifested from the chip (FPGA), to the board, to the box, to the system, and the system-of-systems
  - A wide range of human-robot mixtures, including fully automated platforms, human supported platforms, self reconfigurable hardware, evolvable software
  - Key technology challenges associated with these concepts to regain maximum functionality and operability
  - General discussion of various types of concepts; identification of ongoing concept studies, programs, etc. Technology forecasting and assessment

Working Session 3

In-Space Repair Research
Work Breakdown Structure Areas

- Repair Materials Research
- Repair Processes
- Repair Technology
- Repair Concepts
- Repair Tools, Facilities, and Infrastructure
- Self-Sufficient Space Systems
- Self Diagnostics and Healing
- Structure Reconfiguration to undo the effect of damage
- Materials Transformation
- Others?

Implementation Process

- This package provides summary information on the process to assess the state of the technology, identify the challenges and develop the roadmaps
- A high level 'strategic perspective' is provided as a starting point, followed by specific themes and elements, organized within a hierarchical work breakdown structure
- The motivation for undertaking the development of these road maps is to better understand the full scope of challenges in technologies, concepts, systems demonstrations, and eventual advanced systems that would be necessary to realize the goal of deploying (over time) research and technologies for our future in space
- Based on these road maps, a variety of strategic and (eventually) programmatic planning exercises will be pursued…

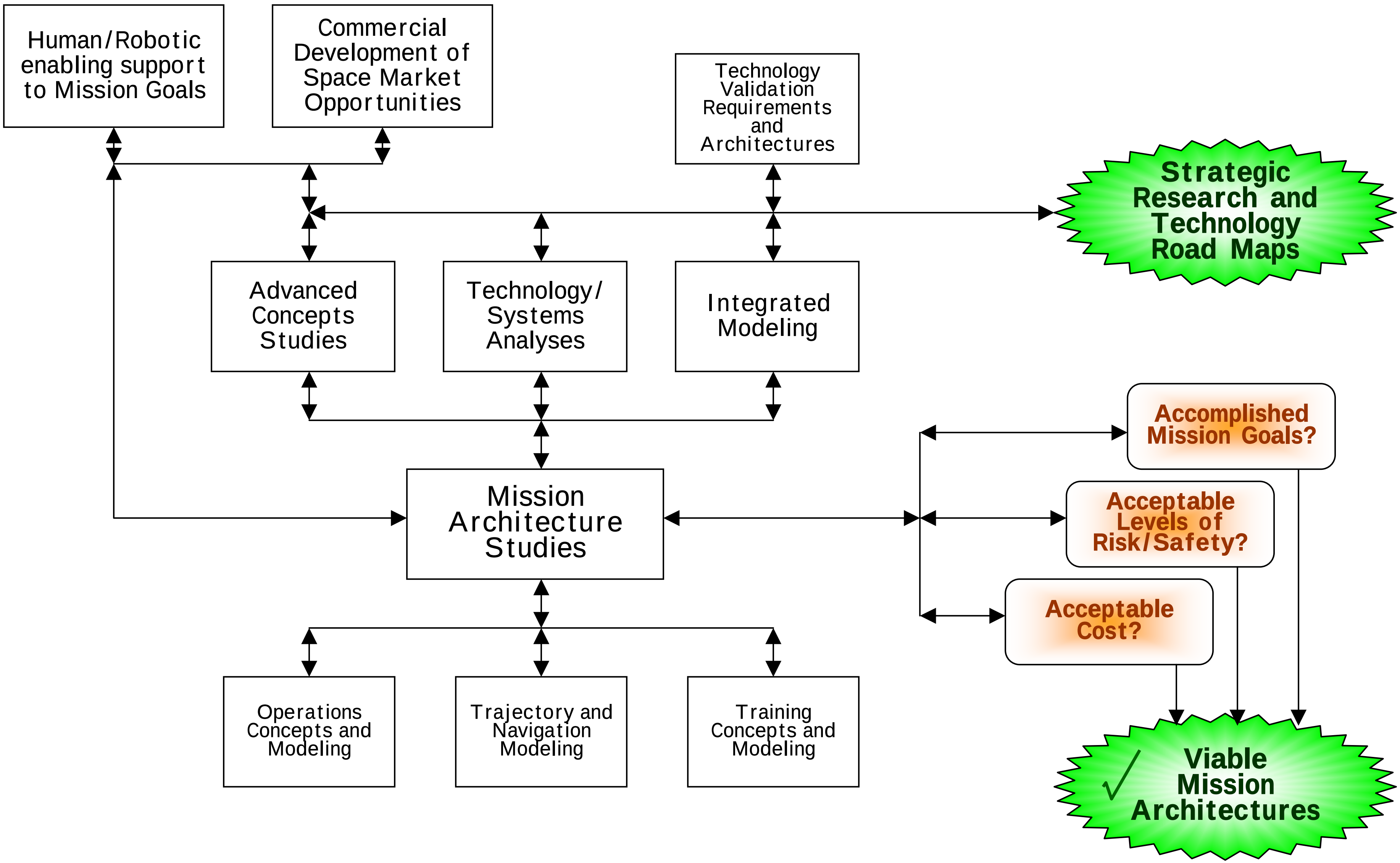
Work Breakdown Structure

- In-Space Fabrication and Repair Research
  - 1.0 Capabilities, Analysis, Concepts, Modeling For F&RR Under Microgravity
  - 2.0 Enabling Advanced Research and Technology
    - 2.1 In-Space Fabrication
    - 2.2 In-Space resources Utilization
    - 2.3 In Space Repair
    - 2.4 Materials
    - 2.5 Facilities
    - 2.6 Environmental Conditioning
    - 2.7 Surface preparation and Conditioning
  - 3.0 Technology Flight Demonstrations

FY 2003 Draft

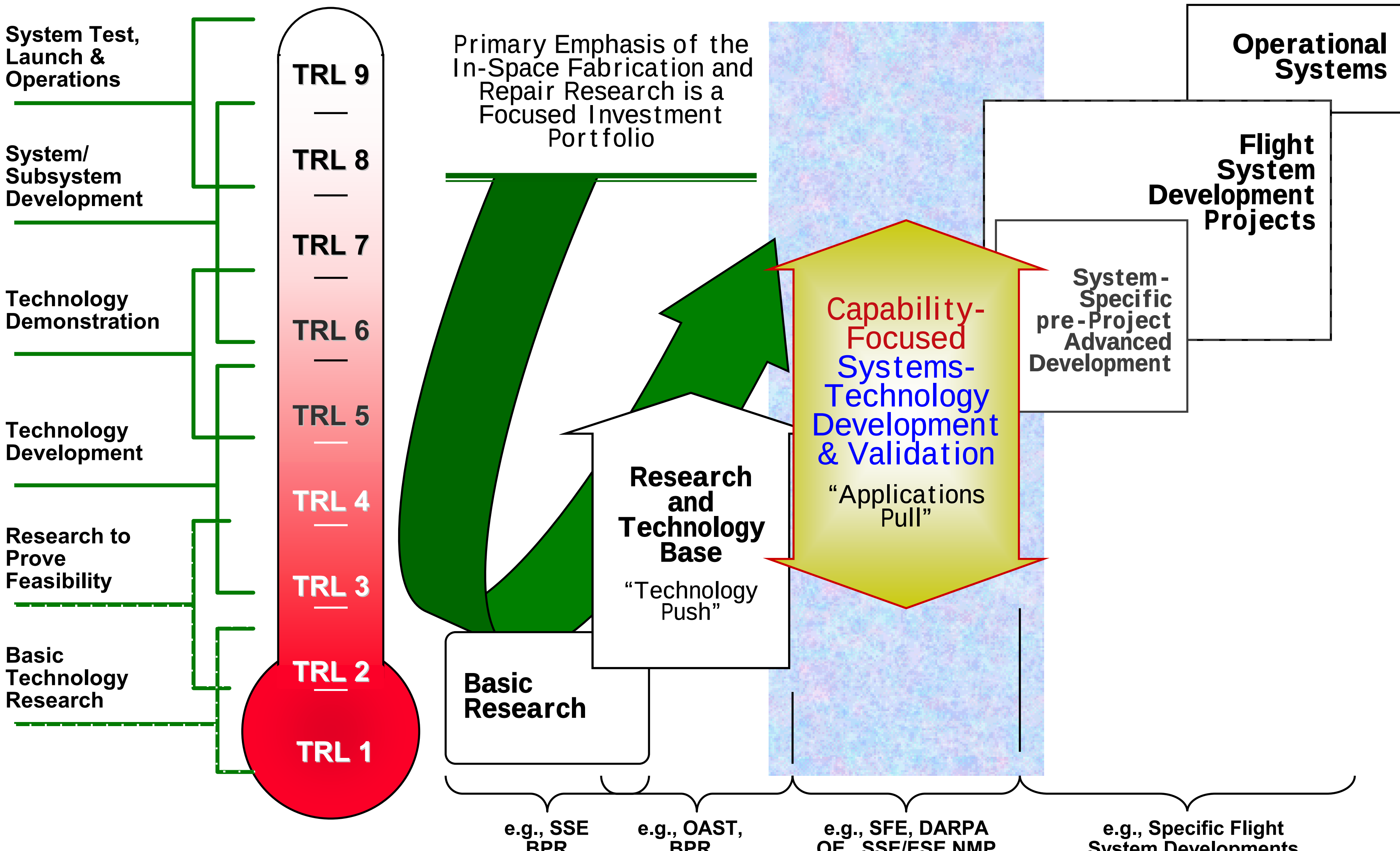
Capabilities Integration, Analysis and Modeling

Integrated Approach

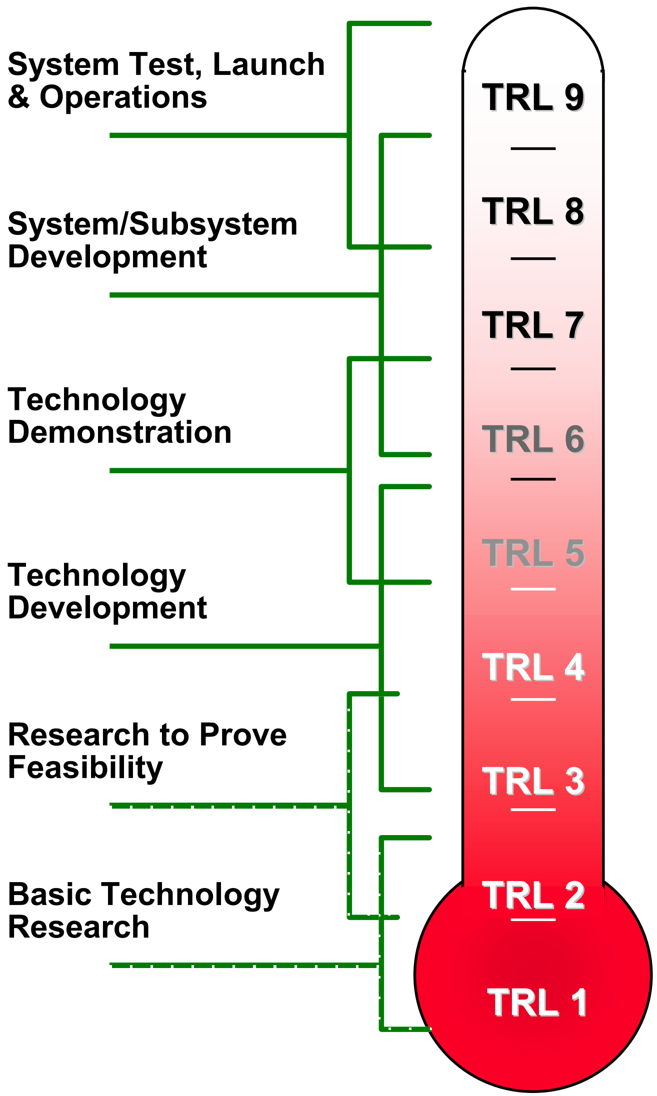


In-Space Fabrication and Repair Research

Technology Development Strategy



Technology Readiness Levels (TRL)



Actual system “flight proven” through successful mission operations

Actual system completed and “flight qualified” through test and demonstration (Ground or Flight)

System prototype demonstration in a space environment

System/subsystem model or prototype demonstration in a relevant environment (Ground or Space)

Component and/or breadboard validation in relevant environment

Component and/or breadboard validation in laboratory environment

Analytical and experimental critical function and/or characteristic proof-of-concept

Technology concept and/or application formulated

Basic principles observed and reported

Assessing Program "Technical Uncertainty"
R&D "Degree of Difficulty" (R&D³)

R&D³ DESCRIPTION

I → **Very low degree of difficulty anticipated in achieving research and development objectives for this technology;** only a single, short-duration technological approach needed to be assured of a high probability of success in achieving technical objectives in later systems applications

II → **Moderate degree of difficulty anticipated in achieving R&D objectives for this technology;** a single technological approach needed; conducted early to allow an alternate approach to be pursued to be assured of a high probability of success in achieving technical objectives in later systems applications

III → **High degree of difficulty anticipated in achieving R&D objectives for this technology;** two technological approaches needed; conducted early to allow an alternate subsystem approach to be pursued to be assured of a high probability of success in achieving technical objectives in later systems applications

IV → **Very high degree of difficulty anticipated in achieving R&D objectives for this technology;** multiple technological approaches needed; conducted early to allow an alternate system concept to be pursued to be assured of a high probability of success in achieving technical objectives in later systems applications

V → **The degree of difficulty anticipated in achieving R&D objectives for this technology is so high that a fundamental breakthrough in physics/chemistry/etc. is needed;** basic research in key areas needed before feasible system concepts can be refined

Research and Development Degree of Difficulty

R&D^3 1	**P(Success) ≥ 90-95%** *Requires 1-2 Paths to Assure Success*
R&D^3 2	**P(Success) ~ 80-90%** *Requires 2-3 Paths to Assure Success*
R&D^3 3	**P(Success) ~ 70-80%** *Requires 3-4 Paths to Have a Good Chance of Success*
R&D^3 4	**P(Success) ~ 50-60%** *Requires 4-5 Paths to Have Reasonable Chance of Success*
R&D^3 5	**P(Success) ≤ 20-30%** *Requires 6-8 Paths to Have Some Chance of Success*

Focusing on Enabling Capabilities

Targeted Basic Research in Key Materials and Processes leading to Technology and Applications Concepts at a Low Level of Funding

Starting Point: TRL 1/2

Many, Diverse Competing Technologies at a Low Level of Funding -- All Addressing Approximately the same functional capabilities…

Starting Point: TRL 3/4

Where Necessary, Technology Flight Experiments

Several Competing Technologies at a Moderate Level of Funding

Goal: TRL 5

In Most Cases 1 or 2 "Best Candidate" Technologies at a Substantial Level of Funding

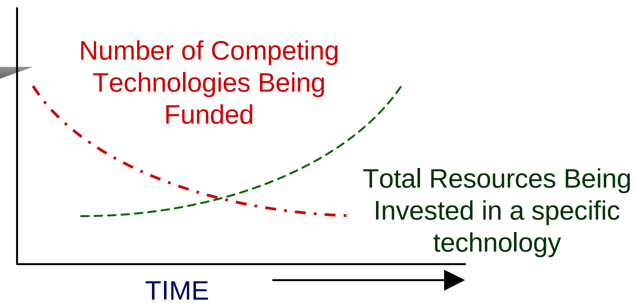
Goal: TRL 6

Where Needed 1 or 2 "Best Candidate" Systems-Level Technology Flight Demos at a Significant Level of Funding

Goal: TRL 7

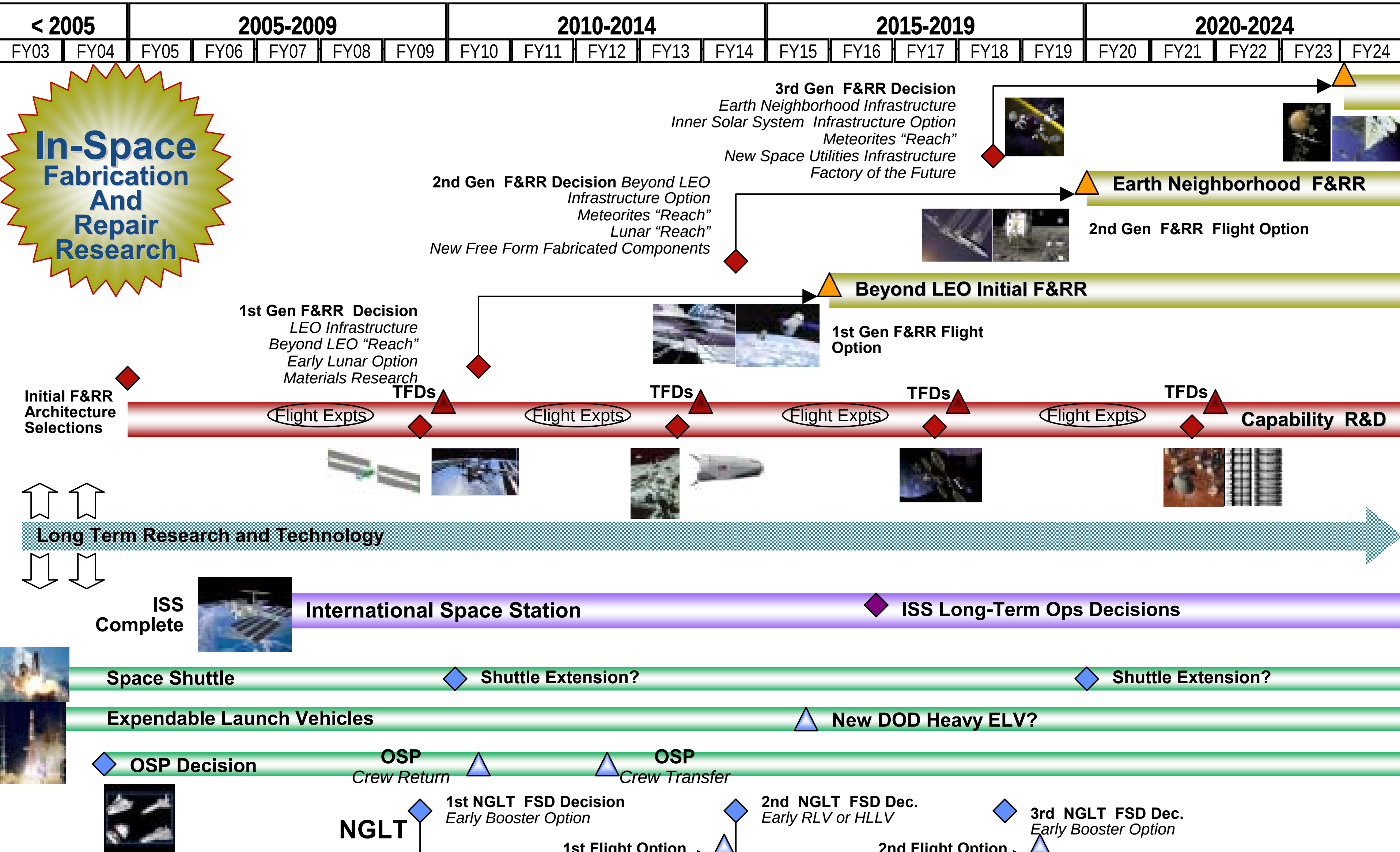
Technology Ready to Support Decisions to Proceed with Development of The Desired Capability…

Technologies Dropped or Deferred to Future Application Opportunities



Integrated Strategy for In-Space Fabrication and Repair Research

(Notional Draft - 23 June 2003)



What *Might* Be Accomplished in the Next Decade?

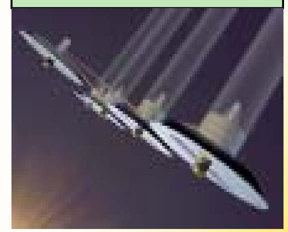
2- to 5- Fold
"Factors-of Improvement"
in Several Key Earth Neighborhood Space Systems Capabilities*

* In conjunction with key Collaborative Investments…

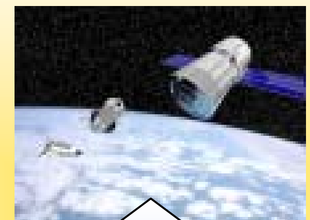
- Increased Available Power at Reduced Cost for Earth Neighborhood Space Systems
- Extension of Effective Operational Lifetime for Systems Beyond Low Earth Orbit
- Improvement in Fuel Efficiency for Transportation in the Earth's Neighborhood
- Reduction in Operations and Logistics Costs
- Increase in the Scale of Systems Beyond LEO (without New Launchers)
- ***What ELSE Might be Accomplished??***

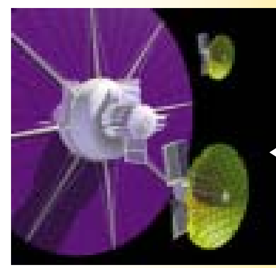
In-Space Fabrication & Repair Research

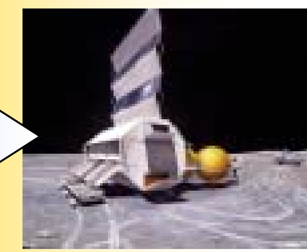
Space Science Missions



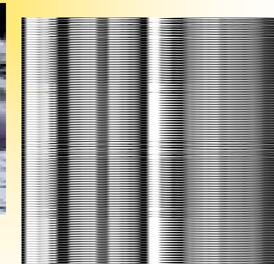
Communications Satellites







National Defense Systems



New Industries

IMPLEMENTATION APPROACH INPUT TEMPLATES

- **This package provides a working "template" for inputs to the In-Space Fabrication and Repair Workshop process.**
  - This package is provided at the THEME Level, HOWEVER, the same information is requested for EACH ELEMENT within each Theme (thus providing a consistent, hierarchical dataset)
- **Components of the Template include:**
  - Summary Quad Chart
  - Assessment of current relevant investments
  - Summary of Strategic Technical Challenges (and Unknowns) being addressed
  - THEME (or ELEMENT) Work Break Down Structure -- going down to the next level in the WBS
  - Research & Technology Schedule of Milestones
  - Summary of Anticipated Deliverables / Benefits (after 5 years and 10 years)
  - Back Up Data -- some examples given; can be otherwise. Should include
    - Technology Metrics
    - Chart indicating How the Theme (or Element) will support the high-level goal of better Architectures
    - Strategic R&T Approach Chart ("Bubble Chart")
    - General <TBD> "Cycle of Innovation" Sequence

A-WBS_Element (Fabrication) or Sub-Element Name (Free-Forming Fabrication

Overview

Objective(s)
- TEXT

Approach
- TEXT

Anticipated Participants
- TEXT

Major Milestones

Date Milestone Description

Potential Testbed Utililzation/Requirements
- TEXT

Expected Applications/Benefits
- TEXT

PICTURE(S)

A-WBS_Element or Sub-Element Name

Assessment of Current/Planned Investments

- **CURRENT RESEARCH PROGRAMS ASSESSMENT (Non-NASA)**
  - TITLE
    - DESCRIPTION
    - KEY MILESTONES / DELIVERABLES
    - PARTICIPANTS and/or POINTS OF CONTACT
    - LEVEL OF FUNDING (IN FY 03-05)
  - TITLE (etc.)
    - Etc.

- **CHALLENGE RESEARCH PROGRAMS IDENTIFICATION**
  - TITLE
    - DESCRIPTION
    - KEY MILESTONES / DELIVERABLES
    - PARTICIPANTS and/or POINTS OF CONTACT
    - LEVEL OF FUNDING by other Agencies
  - TITLE (etc.)
    - Etc.

Repeat for as many pages as needed; Informative images, illustrations or figures should be "embedded" if available

A-WBS_Element or Sub-Element Name

Strategic Technical Challenges

Challenges

- Maximize benefit of using resources, in the shortest amount of time, while minimizing Earth delivered infrastructure and maintenance
  - Economical (power & Earth supplied equipment and consumables) production of propellants and other usable materials from lunar regolith
  - Long-duration operation in extreme environments (ex. 500 days on Mars surface for propellant production)
  - High reliability due to no (or minimal) maintenance capability for pre-deployed and robotic mission applications
  - Autonomous control and failure recovery for non-[illegible] monitoring (for pre-deployed and robotic missions) and to minimize crew involvem[illegible]
  - Efficient excavation of resources in extre[illegible] (ex. Lunar permanent shadows), dusty/abrasive, and/or micro-g environments (Asteroids, [illegible], Mars moons, etc.)
  - Processing and manufacturing techniques capable of producing 100's to 1000's their own mass of product in their useful lifetimes, with reasonable quality.
  - Construction and erection techniques capable of producing complex structures from a variety of available materials.
  - In-situ manufacture of parts and equipment with the minimum of required equipment and crew training

Unknowns

- Is water/ice, hydrogen, or both located in lunar polar and permanently shadowed crater? Is the ice/hydorgen accessible/useable?
- How much water is in the Mars regolith and can it be efficiently extracted? Is subterranean water present, what form is it in, and where?
- What are the material chemical and physical properties of NEO asteroids? How much water is available and in what form/concentration is it found (ice, hydrated clays, …)?

A-WBS_Element or Sub-Element Name

Strategic Technical Challenges

Challenges(list)

Unknowns(list)

Name the Challenge:

- **Recommend the research options to address each of the challenges identified:**

A-WBS_Element or Sub-Element Name

Technology Assessment (1 of 2)

Example

	Technology / Discipline Metrics				R&D Metrics***		Notes/Comments
	Characteristics and/or Functional Area	Current*	Goal	Time Frame?**	Current TRL	Expected R&D³	
Thin Film Cells on Flexible Substrates	Efficiency	10%	15%	Near-Term	4	2	
			20%	Mid-Term	3	2	
			25%	Far-Term	2	3	
	Power per unit mass	150 W[illegible]	250	Near-Term	4	2	
			[illegible]	[illegible]-Term	3	2	
			[illegible]	Far-Term	2	2	
	Power per unit mass			Near-Term	4	2	
				Mid-Term	3	2	
				Far-Term	2	2	
				Near-Term			
				Mid-Term			
				Far-Term			

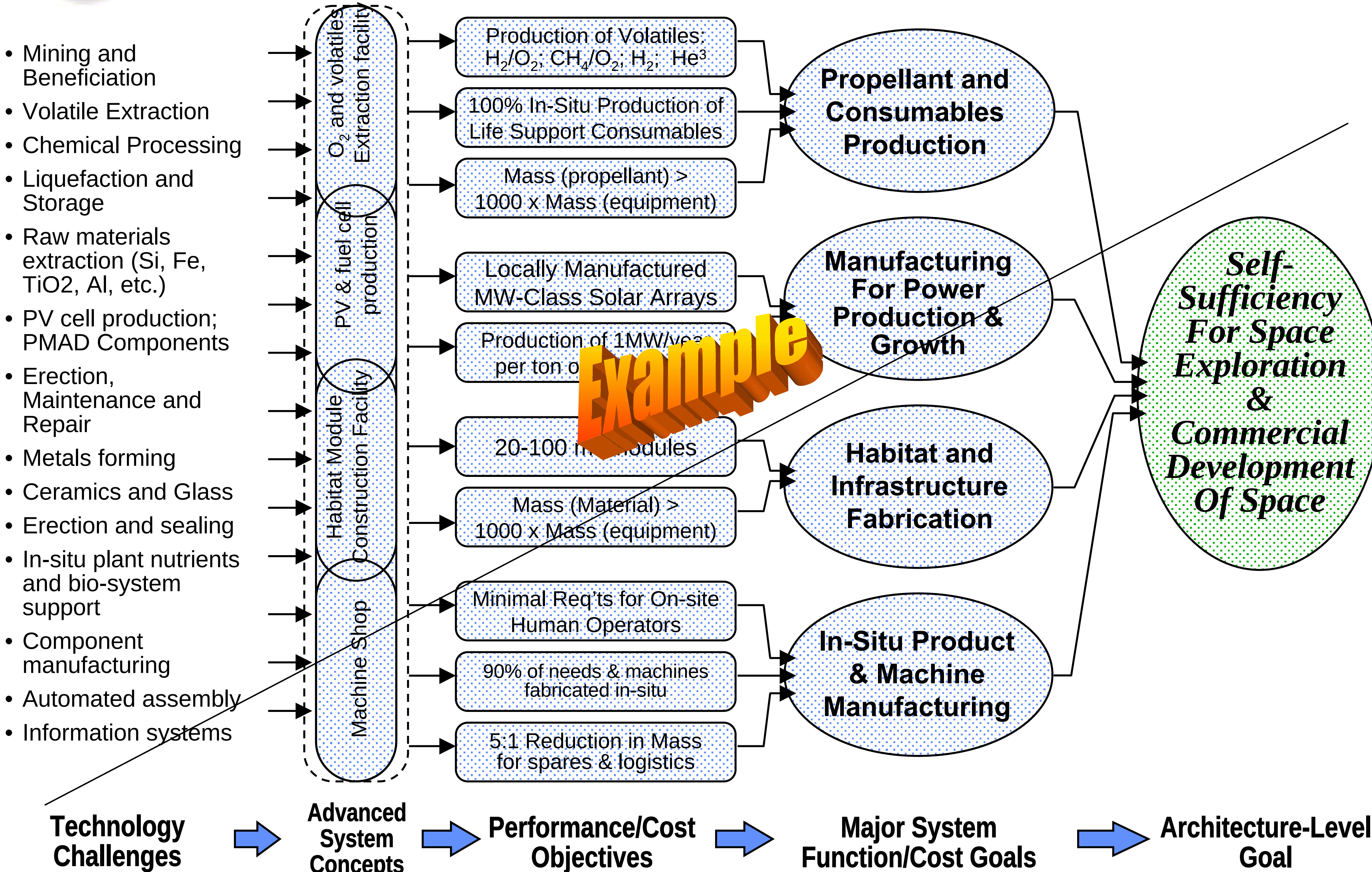
NOTE:
* In a flight system (or very near-flight system, such as a major prototype ground test) application
**For each relevant timeframe (as appropriate); nominally achieving TRL 6 by that time frame
*** Where theTRL and R&D³ are stated for the Technology / Discipline Metrics Goal in Question

Technology Assessment (1 of 1)

Technology	Technological Approach(es) to Achieving Goal?		Potential Applications and/or Benefits
	Characteristics and/or Functional Area	Technological Approach(es)?	

A-WBS_Element or Sub-Element Name

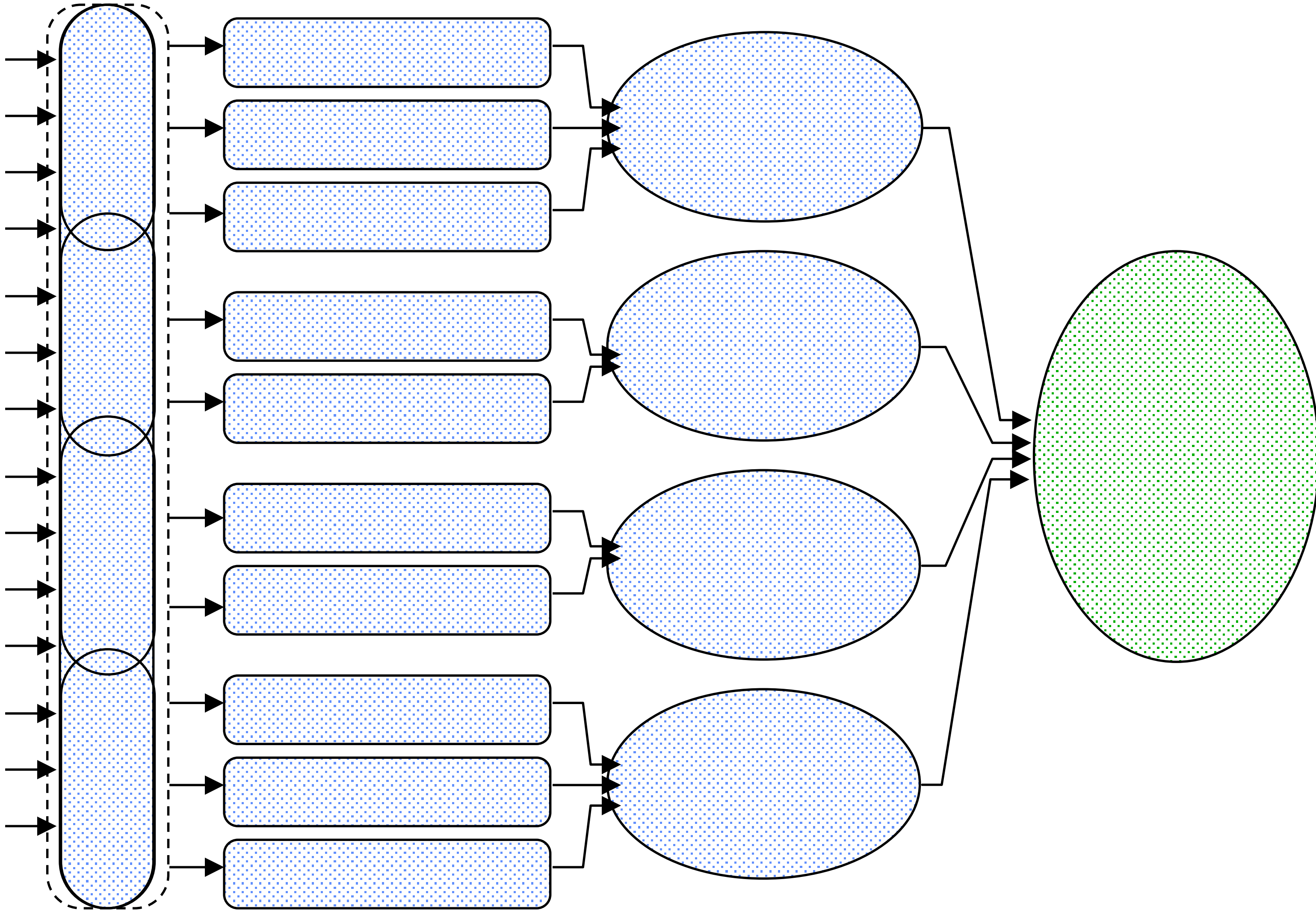
Strategic Research & Technology Approach



A-WBS_Element or Sub-Element Name

Strategic Research & Technology Approach

- Mining and Beneficiation
- Volatile Extraction
- Chemical Processing
- Liquefaction and Storage
- Raw materials extraction (Si, Fe, TiO2, Al, etc.)
- PV cell production; PMAD Components
- Erection, Maintenance and Repair
- Metals forming
- Ceramics and Glass
- Erection and sealing
- In-situ plant nutrients and bio-system support
- Component manufacturing
- Automated assembly
- Information systems



Technology Challenges → **Advanced System Concepts** → **Performance/Cost Objectives** → **Major System Function/Cost Goals** → **Architecture-Level Goal**

A-WBS_Element or Sub-Element Name

R&D Products / Benefits Summary

Example

5 Years

- 50m Ultra Lightweight Structures and Optics for Large Aperture Observatories, Solar Sail, Interferometers
- 200 Watts/kg SPG for Earth Science, Space Science & Commercials
- Ground to Space Power Beaming for Space Science
- Tether System Application for Transportation, Power Generation and Rotating System
- High-Efficiency Energy Storage Systems (e Regenerative Fuel Cells, Flywheels, etc.)
- High Temp. Devices/Materials for Space Science
- Wireless Power Transmission (WPT) for Commercial Applications, including High Efficiency and Low Cost Microwave Devices
- Highly Automated Ground & Space Systems Operations (System Management)
- High Efficiency PV Arrays for Domestic Use
- Advanced Cryogenic Propellant R&D results
- Automated Systems for Manufacturing
- Intelligent Smart Systems for Commercial Applications

10 Years

- Flight Demonstrated 100 kW solar power (Space Science, Commercial Space, HEDS) and nuclear reactor power systems (for surface applications)
- 200 meters Lightweight Structures and Optics
- 1kW/kg SPG technology (in the lab)
- Ground-to-Space & Space-to-Space Power Beaming for Interstellar, Space Exploration Resources Utilization & Asteroid Retargeting
- ass SSP (including EPS) for HEDS
- Non-nuclear Deep Space Power
- 100-1000kW Power Utility in Space
- Scalable Cryogenic Propellant Depot for commercial and government use
- Power Utility in Space
- Advanced Spacecraft Servicing for Earth & Space Science Missions
- Very High Temp. Devices/Materials for HEDS
- Long Life Space Materials/Component Systems
- Support Very Low Cost Space Launch
- High Efficiency PV Arrays for Commercial Use
- Large-Scale Low Cost Manufacturing for Components/ Systems

A-WBS_Element or Sub-Element Name

R&D Products / Benefits Summary

5 Years	**10 Years**